A "CONVENTIONAL" ACCELERATOR SYSTEM FOR
INERTIAL FUSION USING HEAVY ION BEAMS

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Several accelerator systems[1,2,3] have been proposed for
accelerating heavy-ion beams to be used for inertially confined
fusion. All these proposed schemes involve some rather large
extrapolations of the state-of-the-art in accelerator tech-
nology. Parametric studies of accelerator systems[4] made during
the 1976 ERDA Summer Study in Oakland, California, indicated
that by a combined application of appropriate accelerator types
and techniques it should be possible to design an accelerator
system with little or no extrapolation of the performances of
components beyond those which have already been achieved on
existing machines. It is much too early to concentrate on any
specific machine design at this time, nevertheless it is useful
to go through the exercise of designing one such accelerator
system. The effort will ensure that no crucial considerations
were overlooked in the gross parametric studies and that the
various accelerator components and techniques employed do, indeed,
fit together properly. This exercise could also serve to further
refine the optimization of the parameters.

In proceeding with this exercise, by implication we are
ignoring the problem of the lifetime of the charge state of the
ions. Although no theoretical or experimental data are available,
indications are that the lifetime due to charge exchange between

ions in the beam is short compared to the acceleration time in a conventional synchrotron. If this is indeed the case, the only viable candidate for an accelerator would be the linac. In this paper we will simply ignore this problem and assume that the lifetime is adequately long.

The final beam transport from the accelerator to the target is another crucial problem for which further detailed studies are needed. However, this is outside the scope of this report. The design given here will be carried only to the point where the beam is extracted from the accelerator.

Space-charge neutralization may be employed to reduce the focusing strength required or to attain beam current beyond that given by the conventional space-charge limit. But further investigation is needed to be able to apply this technique properly. In this design we will constraint the beam current to be always below the value given by the vacuum space-charge limit.

To further simplify this design effort we will ignore the details of the pulse shape required. The desired pulse has a long low-power leader and rises sharply at the end of the leader to a high peak value which is maintained constant over a short duration. Approximately 60% of the total beam energy is contained in the peak power portion of the pulse. Here, we will concentrate only on delivering the required energy within the required duration of the peak pulse. This simplification will be further clarified in the discussion below on targetting requirement.

A. Targetting requirement

The requirements (peak pulse only) suggested during the 1976 ERDA Summer Study are:

Peak power = 600 TW

Duration of peak power = 10 nsec

Beam energy at peak power = 6 MJ

   (Total including the leader pulse = 10 MJ)

Specific total energy deposition = 30 MJ/g

Number of beams = 2 to 100

Beam spot radius on target > 1 mm

It was pointed out at the Summer Study that these requirements
are most easily fulfilled by using the heaviest ion at the lowest
charge state, namely U^{+1}_{238}. We further choose an ion energy of
150 GeV and two beams. This gives a current of 2000 A for each
beam. Assuming gold as the target material we get a range[5] of
5 g/cm^2 for 150-GeV U ions. Thus the target thickness must be
> 2.6 mm. The specific total energy deposition, then, requires
a beam spot radius of 1.03 mm. Higher ion energy will lead to
a beam spot radius smaller than the specified lower limit of
1 mm.

In addition we assume that the last focusing element has an
aperture radius of 30 cm and is situated 10 m away from the
target. This gives the maximum allowable transverse and longi-
tudinal emittances (normalized) defined in Ref. 4,

$$\begin{cases} \dfrac{\varepsilon_t}{\pi} = 4.14 \text{ cm-mrad,} \\[2em] \dfrac{\varepsilon_\ell}{\pi} = 552 \text{ cm-mrad.} \end{cases}$$

We also check that the ratio of the space charge term to the
emittance term at the beam spot on target is k = 0.00025 so that
the space-charge effect there is negligible.

Each 2000-A beam can be composed of several branches all aimed at the same spot on target. If the last focusing elements of the branch beams are separated laterally by no more than 1 m, the angle between branches is less than 0.1 rad and the overlap of the branches throughout the penetration depth of 2.6 mm in the target is essentially perfect.

B. Development of Parameters of the Accelerator System

We assume that the U_{238}^{+1} ions are produced in a conventional duoplasmatron source and are initially accelerated to an energy T_i with beam current I_i in a conventional rf-linac. The beam is then multi-turn injected (current magnification S) into a synchrotron where it is further accelerated to the final energy $T = 150$ GeV (current magnification A) and bunched by the synchrotron rf-system (current magnification C) into 2K bunches each 10 nsec long. These bunches are extracted, transported and focused to hit the target simultaneously on two spots, K bunches each. The current requirement then specifies

$$SxAxCxKxI_i = 2000 \text{ A} .$$

The parameters of such an accelerator system are developed in a more-or-less logical and unique manner from a set of assumed hardware performances. The assumed performances are boxed and the chosen parameters are underlined.

We start with the final requirements

$$U_{238}^{+1} \text{ ions at} \begin{cases} T &= 150 \text{ GeV} \\ \beta &= 0.8026 \\ \beta\gamma &= 1.3456 \\ B\rho &= 9952 \text{ kGm} = \text{magnetic rigidity} \end{cases}$$

current of each of 2 beams = 2000 A

and develope the parameters backwards toward injection.

1. Synchrotron radius

Superconducting magnets are preferred because of the high field intensity and the low power consumption which is important for an efficient power plant. We assume

> max. bending dipole field $\cong$ 50 kG
>
> dipole packing factor $\cong$ 65%

Such dipoles have been built with conventional NbTi conductors. This gives directly

$$\text{ring radius} \quad R \cong 310 \text{ m} \ .$$

We shall choose a round number for the ring circumference, namely

$$2\pi R = 2000 \text{ m} \quad \text{and} \quad R = 318.3 \text{ m} \ .$$

2. Maximum beam current

The space charge tune shift $\Delta\nu$ is given by

$$\Delta\nu = \frac{e^2}{mc^2} \frac{1}{(\beta\gamma)^2} \frac{I}{ec} \frac{R}{\epsilon_t/\pi} \ . \tag{1}$$

For $\Delta\nu < \frac{1}{4}$ this gives

$$\text{space charge limited current} = 450 \text{ A}.$$

Hence we take, after bunching

$$I = 400 \text{ A} \quad \text{and} \quad K = 5 \ .$$

3. Bunching factor

The choice of bunching factor C depends on the details of the bunching scheme and the peak voltage of the rf system in the synchrotron. It can only be justified a posteriori by the coherence of the parameters. Here we choose what will be shown to be a reasonable value of

$$\underline{C = 40}$$

Therefore, before bunching I = 10 A.

The total length of bunched beam required is $2K\beta c(10 \text{ nsec}) = 24$ m. Before bunching it is 40 x 24 m = 960 m. Thus, even with high-field superconducting magnets the synchrotron is still large enough to serve as the igniter for two reactors.

4. Injection energy into synchrotron

If at injection $\frac{v}{c} = \beta_i$, the beam current will be $\frac{\beta_i}{\beta} \times 10$ A = $12.5 \ \beta_i$ A. The space charge tune shift is, then

$$\Delta\nu = \frac{e^2}{mc^2} \frac{1}{\beta_i} \frac{12.5 \text{ A}}{ec} \frac{R}{\epsilon_t/\pi}$$

where we have put $\gamma_i \cong 1$. For $\Delta\nu = \frac{1}{4}$ and with R = 318 m, $\epsilon_t/\pi = 4.14$ cm-mrad this gives $\beta_i = 0.052$ corresponding to an energy of 300 MeV. The injection energy should be somewhat higher, especially since the beam will be bunched as it is accelerated by the rf. Therefore, we choose the injection energy

$$\underline{T_i = 500 \text{ MeV}} \quad \begin{cases} \beta_i & = 0.06704 \\ \beta_i\gamma_i & = 0.06719 \end{cases} .$$

5. Acceleration current magnification

The current magnification due to acceleration is, then

$$A = \frac{\beta}{\beta_i} = 12.0$$

and the current in the synchrotron after S-turn injection should
be

$$SI_i = \frac{10}{12.0} A = 0.833 \ A \ .$$

6. Multiturn injection

We assume a current from the linac at 500 MeV of about

$$\boxed{\text{linac current = 50 mA}} \ \ .$$

This shows that we must choose a multiturn injection of

$$\underline{S = 16}, \quad \text{hence} \quad \underline{I_i = 52 \ mA} \ .$$

The overall current multiplication is now

$$SxAxCxKxI_i = 16x12x40x5x0.052 \ A = 2000 \ A.$$

7. Preaccelerator energy and current

We take a conventional Cockcroft-Walton D.C. generator as
the preaccelerator for injection into the low-β section of the linac.
The chosen energy and current are

$$\underline{T_o = 833 \ keV} \quad \text{and} \quad \underline{I_o = 80 \ mA} \ .$$

These choices will be justified later.

The whole set of overall parameters is summarized below:

<u>Preaccelerator</u>

$$T_o = 833 \ keV$$

$$I_o = 80 \text{ mA}$$

Linac

$$T_i = 500 \text{ MeV}$$

$$I_i = 52 \text{ mA}$$

Current transmission = 65%

Synchrotron

Radius R = 318.3 m

Circumference $2\pi R$ = 2000 m

Injection

$$T_i = 500 \text{ MeV}$$

16-turn injection (S = 16)

Current = SI_i = 0.833 A

Final unbunched

T = 150 GeV

Velocity ratio = 12 (A = 12)

Current = ASI_i = 10 A

Final bunched

Bunching factor = 40 (C = 40)

No. of beam segments = 20

Length of segment before bunching = 100 m

Length of segment after bunching = 25 m (~10 nsec)

Current I = $CASI_i$ = 400 A

Targetting

No. of branches per beam = 5 (K = 5)

Current per beam = KI = 2000 A

No. of beams per target = 2

No. of targets (reactors) = 2

We now proceed to examine the designs of component systems.

C. Linac and Preaccelerator

   1. High-β linac section

       This section has the conventional standing wave drift-tube structure with quadrupole magnets inside drift tubes for transverse focusing. This structure works well above 100 MeV. However, the lowest energy that can be handled by such a structure is limited by the strength of the quadrupoles. To extend the lower limit, we choose at the low energy end a low rf frequency of 25 MHz (wave length λ = 12 m), a low acceleration rate (peak average accelerating field E_o = 2 MV/m), and a $2\beta\lambda$ periodicity. The average rf radial defocusing is, then, ($\gamma \cong 1$ non-relativistic)

$$\left(\frac{r''}{r}\right)_{rf} = \frac{eE_o}{mc^2\beta^2}\ \frac{1}{\beta\lambda}\left[\frac{\sin\ \pi\frac{g}{\beta\lambda}}{\frac{g}{\beta\lambda}}\ \tan\ (-\phi_s)\right]$$

$$= \frac{1.23\times10^{-10}}{\beta^3}\ cm^{-2} \qquad (2)$$

where r''/r denotes the relative longitudinal variation of the beam radius and where for numerical values we have taken a gap length of $\frac{g}{\beta\lambda} = \frac{1}{4}$ and a synchronous phase of $\phi_s = -30^o$. The space charge radial defocusing is

$$\left(\frac{r''}{r}\right)_{sc} = \frac{2e^2}{mc^2\beta^2}\ \frac{I_b}{\beta ce}\ \frac{1}{r^2} = \frac{0.85\times10^{-10}}{\beta^3}\ cm^{-2} \qquad (3)$$

where

   I_b = bunched beam current

      = (average current 52 mA) x (bunching factor 6)

      = 0.312 A

and r = average beam radius = 1 cm.

For quadrupoles we choose a length $\ell = \frac{4}{3} \beta\lambda$, a field
gradient B' = 8 kG/cm, and the +-+- arrangement. The average
radial focusing provided by the quadrupoles is, then, approximately

$$\left(\frac{r''}{r}\right)_Q = -\frac{5}{36}\left(\frac{eB'\ell}{mc^2\beta}\right)^2 = -0.66\times10^{-4} \text{ cm}^{-2} . \qquad (4)$$

This amount of focusing can compensate for the combined rf and sc
defocusing down to

$$\beta = 0.015 \quad \text{or} \quad T = 25 \text{ MeV} .$$

Thus, we can use this structure from 30 MeV to 500 MeV. At
higher energies one can go to higher rf frequencies to reduce the
cavity diameter and/or to higher average accelerating field E_o to
reduce the length. An overall average acceleration rate of
2 MeV/m is attainable. The total length of the high-β section is,
then, about 240 m.

The detailed design of this linac section is laborious but
straight-forward. There is no point going into this effort here.

2. Low-β linac section

Below 30 MeV the quadrupoles assumed are inadequate to
provide radial focusing. We can contemplate stronger quadrupoles,
but it is more appropriate to use a different structure. Several
alternative low-β structures are available, such as the Wideröe
structure, the spiral or split-ring structure, and the alternating-
phase-focusing (APF) structure[6]. As an example, we will consider
here an APF low-β section.

The dynamics of beams in APF structures is studied in
Ref. 6 without taking into account space-charge effects. But for

the parameters we will adopt, the rf forces dominate; hence the

results of computations given in Ref. 6 should be adequate for

a first-order approximate design.

We will use the APF structure to span a factor 36 in energy

from 0.833 MeV to 30 MeV or a factor 6 in β. With uniform

accelerating field E_o an APF section can only span a factor of

about 2 in β. Thus, E_o must increase by a factor 3 from the

beginning to the end of this section. Taking an 8-gap periodicity

given in Ref. 6 we obtain the following parameters for the APF

section.

Gap phases	(-90°, -30°, 30°, 90°, 90°, 30°, -30°, -90°)
RF frequency	25 MHz
RF wave length λ	12 m
Energy range T	0.833 MeV to 30 MeV
β range	0.00274 to 0.01645
Average field range E_o	2.35 MV/m to 7.05 MV/m
Accelerating rate range	0.714 MeV/m to 2.14 MeV/m
Normalized radial acceptance (1 cm radius hole)	3.2 π cm-mrad
Full phase acceptance $\Delta\phi$	70°
Full momentum acceptance $\Delta p/p$	0.019
Shortest cell	2.74 cm
Total length	20.4 m

The radial acceptance of the structure is more than adequate to

contain the estimated transverse beam emittance of ε_t/π = 0.1 to

0.2 cm-mrad. The full momentum spread of the beam which fills

the longitudinal acceptance at 833 keV (because of the use of

a buncher) will scale as $p^{-5/4}$ to

$$\frac{\Delta p}{p} = 3.5 \times 10^{-4} \quad \text{at} \quad 500 \text{ MeV} .$$

It is possible to divide the total length into, say, 3 shorter cavities with different focusing periodicities so that E_O may remain uniform throughout. In this case, matching between cavities in both longitudinal and transverse phase spaces must be properly arranged. Unless shorter cavities are desirable because of some practical conveniences such as power matching to available rf power tubes, the cavity tilting of a factor 3 is not difficult to achieve and the length of 20 m is not excessive for construction.

At the end of this section the beam must be matched both longitudinally and transversely into the high-β section. This can be accomplished in the usual manner using quadrupoles and a bunching (or debunching) cavity.

3. Preaccelerator and ion source

The 833 kV Cockcroft-Walton and the accelerating column are standard items. The use of a duoplasmatron source for heavy ions is common, although the specific experience for U_{238}^{+1} ions is limited. Nevertheless, experts agree that it would not be difficult to obtain an 80 mA current.

One problem deserving some discussion is the transporting and focusing of this highly space-charge dominated beam from the preaccelerator. Assuming a beam radius of $r = 1$ cm we get from Eq. (3) a space charge defocusing strength of

$$\left(\frac{r''}{r} \right)_{sc} = 1.05 \times 10^{-3} \text{ cm}^{-2} .$$

At this very low β, it is advantageous to use electrostatic

quadrupoles. To overcome the space charge defocusing we can
use, for example, electrostatic quadrupoles with field gradient
$E' = 20$ kV/cm^2 (equivalent to magnetic quadrupoles with gradient
$B' = \frac{1}{300 \ \beta}$ x 20 kG/cm = 24.3 kG/cm, a rather high value) and
length $\ell = 10$ cm. Eq. (4), then, gives

$$\left(\frac{r''}{r} \right)_Q = -2.0 \times 10^{-3} \ cm^{-2} .$$

There are other less conventional beam transport elements such
as the plasma lens which are much stronger. Furthermore, the
beam is likely to be partially neutralized and the necessary
strength of the transport elements may well be much lower than
indicated above.

A single harmonic buncher should be adequate to bunch
the beam so that at least 65% of the beam falls within the 70°
phase acceptance of the APF linac section.

D.   Synchrotron

1.   Magnet lattice

The most efficient lattice for providing alternating
gradient transverse focusing is that composed of simple FODO cells
with bending dipoles placed in space 0 between quadrupoles F and
D. For simultaneous extraction of 10 bunched beam segments using
the scheme described below it is convenient that the lattice be made
up of 10 identical sectors. In each sector the dipoles after the
F quadrupole in one of the cells are omitted to provide space
(straight section) for the extraction septum magnet. The septum,
hence the space (≅ half-cell length), should be long enough for
deflecting the beam out of the ring. The dispersion function at the
upstream end of the straight section (entrance to the septum)

should be a maximum. The betatron phase advance from the F
quadrupole upstream to the beginning of the septum should be
somewhere between 70° and 90°.

For ease of handling, each dipole should not be much
longer than ~6 m. A drift space of ~3 m should be provided next to
each quadrupole to accommodate beam sensors, rf cavities, correction
magnets, and beam manipulating elements. All these requirements
are satisifed by the sector shown in Fig. 1. Also shown are the
horizontal and vertical amplitude functions β_h and β_v (without
subscript h or v, β denotes the particle velocity v/c), and the
horizontal dispersion function η_h. Parameters of the lattice
elements defined in Fig. 1 are:

	Effective length	Field or gradient	
		Injection (0.5 GeV)	Final (150 GeV)
Quadrupole			
F_0 to F_4	2.8 m	+9.32 kG/m	+186.6 kG/m
D_0 to D_3	2.8 m	-9.32 kG/m	-186.6 kG/m
Dipole			
B	6.1 m	2.44 kG	48.8 kG
Drift space			
G	0.3 m		
H	3.0 m		
L (straight section)	22.2 m		

and the orbit parameters are:

Bending radius ρ	203.9 m
Phase advance per cell μ	78.75°

Betatron tune ν 8.75

Transition energy γ_t 9.0

2. Multiturn injection and aperture requirement

The principal element in the conventional scheme for multi-
turn injection is a septum magnet which transports a new turn of
beam into the synchrotron and lets pass the previously injected turns
of beam on the other (field-free) side of the septum. The septum
should be thin so that the new and the old turns can be stacked
next to each other with a minimum of separation between them. As
successive turns are stacked since it is impossible to move the septum
that rapidly, the orbit of the already injected beam is moved by
a pair of fast orbit-bump magnets located approximately +90° and
-90° betatron phases from the exit of the septum. For the lattice
described it is most convenient to inject vertically with the
vertical septum located in any one of the ten straight sections.
The exit of the septum will be just upstream of D_2 and the bump
magnets should be placed in the 3-m drift spaces just downstream
of D_1 and just upstream of F_4. To stack in both the vertical and
horizontal planes, the orbit at the exit of the septum must be moved
in both dimensions and hence, two pairs of bump magnets, one vertical
and one horizontal, are needed. To inject 16 turns one can stack,
say, 2 turns vertical and 8 turns horizontal or 4 turns each in the
two planes.

There exist other yet untried schemes such as the resonant
injection scheme which may, in fact, be simpler for injecting a large
number of turns. But for only 16 turns the conventional scheme
described above will suffice.

The transverse normalized emittance of the linac beam is

estimated to be 0.1 - 0.2 cm-mrad. The maximum emittance of

4.14 cm-mrad in each plane allowed for targeting is much more

than adequate to contain 16 turns of beam. The emittance of

the stacked beam will, however, be determined by the space charge

detuning. With a stack current of 0.833 A and an allowable tune

shift of $\Delta \nu = \frac{1}{4}$ Eq. (1) gives a required transverse beam emittance

of

$$\varepsilon_t/\pi = 3.18 \text{ cm-mrad} .$$

The largest β_h (or β_v) in the dipoles is 78 m, and hence the largest

beam half width is

$$\left[\beta_h \frac{\varepsilon_t/\pi}{(\beta\gamma)_i} \right]^{1/2} = 19.2 \text{ cm} .$$

We, therefore, need a good field diameter in the dipoles of about

40 cm. To get this in a superconducting magnet the inner diameter

of the coil must be about 55 cm. This is unusually large, but there

is no inherent difficulty in constructing these large aperture

magnets. The extra 15 cm diameter of "poor-field" aperture should

be made available for beam extraction (see below).

    3. RF system and acceleration

        To bunch the beam into 20 segments the rf must have the

harmonic number 20. We choose an acceleration time of $\sim\frac{1}{2}$ sec

which leads to a required peak rf voltage per turn of ~5 MV. The

rf parameters are, then:

Harmonic number h	20
Peak voltage per turn V	5.0 MV
Synchronous phase ϕ_s	50°
Energy gain per turn	3.83 MeV
Acceleration time (0.5 to 150 GeV)	0.494 sec

	Injection (0.5 GeV)	Final (150 GeV)
RF frequency	0.201 MHz	2.41 MHz
Bucket height $\Delta p/mc$		
Stationary	$\pm 0.855 \times 10^{-3}$	$\pm 1.87 \times 10^{-3}$
Moving	$\pm 0.281 \times 10^{-3}$	$\pm 0.615 \times 10^{-3}$
Bucket area* $\Delta\phi\Delta p/mc$		
Stationary	6.84×10^{-3}	15.0×10^{-3}
Moving	0.83×10^{-3}	1.82×10^{-3}
Phase Oscillation frequency		
Stationary	1.26 kHz	0.575 kHz
Moving	1.01 kHz	0.461 kHz

The 25 MHz bunch structure of the linac beam is lost in the process of multiturn injection. Hence, after injection we will have in the synchrotron an essentially d.c. beam with a full momentum spread of $\Delta p/p = 3.5 \times 10^{-4}$ or $\Delta p/mc = 0.235 \times 10^{-4}$. The longitudinal emittance per bunch of such a beam is (in $\Delta\phi\Delta p/mc$ units)

$$\varepsilon_\ell = 2\pi(0.235 \times 10^{-4}) = 0.148 \times 10^{-3}$$

which is much smaller than the bucket areas and the maximum value of $\frac{h}{R} \times 552\pi$ cm-mrad $= 1.09 \times 10^{-3}$ allowed for targetting. To capture this d.c. beam we use the conventional method of adiabatic turn-on. Such a method has been demonstrated to capture all the beam with negligible dilution.

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*In this paper we use the more conventional rf phase $\Delta\phi$ instead of the circumferential length Δs as the abscissa of the longitudinal phase space. They are related by $\Delta s = \frac{R}{h} \Delta\phi$.

The 12:1 frequency modulation range from 0.201 MHz to 2.41 MHz is rather large and may have to be spanned by two rf systems each having a range of 3.5:1. Also, the rather low frequency range means that the physical dimensions of the rf cavities tend to be rather large. To limit the longitudinal dimension we should consider the ferrite-loaded single-gap re-entrant cavities with large transverse dimensions. There are five 3-m drift spaces available in each sector. If we place one cavity in each drift space, there will be a total of 50 cavities, and each cavity must produce a peak voltage of 100 kV. We may be able to crowd two cavities with contiguous gaps in one drift space. Each cavity will then have to produce a 50 kV peak voltage. Even that is quite high in view of the large frequency range. But this is certainly not a fundamental problem. We could have chosen a larger ring circumference and designed a lattice with more drift space to accommodate more cavities. It does not seem to be necessary to make this modification now,before one finds out for sure the highest voltage that can be produced per cavity.

4. Bunching

At the end of acceleration we flat-top the magnets. The half-dimensions $\Delta\phi$ and $\Delta p/mc$ of each beam bunch inside a stationary bucket are given by

$$\frac{\Delta p/mc}{\Delta\phi} = \frac{\pi}{2} \frac{\text{bucket height}}{\text{bucket width}} = \frac{\pi}{2} \frac{1.87\text{x}10^{-3}}{\pi} = 0.935\text{x}10^{-3}$$

and

$$\pi\Delta\phi\Delta p/mc = \text{longitudinal emittance} = 0.148\text{x}10^{-3}.$$

This gives $\Delta\phi = 0.224$ or a bunching factor of $\pi/\Delta\phi = 14$. The simplest way to bunch the beam further to a factor of 40 is by the conventional

method of bunching on the defocusing rf phase.

After flat-topping at 150 GeV the beam bunch is sitting
at ϕ_s = 0. We, first, jump the rf phase by 180° to place the
beam bunch at ϕ_u = π. The beam bunch is shown as the circle a
with radius 0.224 in Fig. 2 where the coordinates are so scaled
that trajectories of phase points for small stable oscillations
around ϕ_s = 0 appear as circles. The beam bunch is then defocused
to compress and stretch along the separatrices to the ellipse b.
We want to compress the minor axis by a factor 14/40. This takes
a time t_u given by

$$\text{Exp}[-2\pi(0.575\text{x}10^3\text{sec}^{-1})\ t_u] = 14/40$$

where $0.575\text{x}10^3$ sec^{-1} is the phase oscillation frequency. This gives

$$t_u = 0.29 \text{ msec .}$$

The rf phase is, then, jumped -180° to place the ellipse b back at
ϕ_s = 0. In $\frac{3}{8}$ of a phase oscillation which takes a time of t_s =
$\frac{3/8}{0.575}$ msec = 0.65 msec, ellipse b will be rotated to ellipse c.
From the construct described we see that ellipse c represents a beam
bunch with a bunching factor C = 40. The total time required is
t_u + t_s = 0.94 msec. It can easily be checked that both the distortion
of ellipse c due to nonlinearities and the deviation of its orien-
tation from exact perpendicular to the $\Delta\phi$ axis due to the graininess
of phase oscillations are quite negligible. After extraction from
the ring the ellipse c will continue to shear during the final
transport to the target. However, the final transport line is, in
all likelihood, shorter than the ring circumference and this final
shear is negligible. In any case, the final shear, if sizeable,

can be allowed for by extracting the beam bunch slightly before
its ellipse has rotated to the vertical position.

In this discussion we have neglected the effect of the
longitudinal space-charge force. This effect will modify the
parameters but will not qualitatively alter the performance of the
scheme. The precisions required throughout the bunching process
are rather minimal and well within the state-of-the-art.

5. Extraction

After bunching the bunched beam current is 400 A. The
space charge limited ($\Delta\nu = \frac{1}{4}$) transverse beam emittance is given
by Eq. (1) to be

$$\varepsilon_t/\pi = 3.8 \text{ cm-mrad.}$$

At the entrance to the extraction septum (Fig. 1) $\beta_h = 78$ m and
the beam half-width is 4.7 cm.

We extract the beam bunches horizontally inward (toward
center of ring). The horizontal extraction septum is placed
19.7 cm inside the central orbit to let pass the injected beam.
The ring magnet lattice is so designed that the horizontal
dispersion function is a maximum, $\eta_h = 11.74$ m, at the entrance
to the septum. With a momentum deficit of

$$\frac{\Delta p}{p} = -\frac{19.7-4.7}{1174} = -1.28\%$$

the orbit is displaced 15 cm inward so that the beam is just passing
next to the septum on the outside. A fast kicker magnet located
one cell upstream of the septum will kick the beam across into the
septum field to be deflected out of the ring.

To kick the beam, say, 10 cm across the entrance to the septum the kick angle must be

$$\frac{10 \text{ cm}}{78 \text{ m} \times \sin 80°} = 1.3 \text{ mrad}$$

where 80° is the betatron phase advance from the kicker to the septum. The total length of the kicker could be 5 m (two 2.5 m sections located in the 3-m drift spaces just up and downstream of F_1). The peak field required is, then, 2.6 kG. The rise time of the kicker can be as long as the time interval between two beam bunches, namely about 0.4 msec. For this relatively slow rise the core of the kicker magnet can be made of thin laminated steel, and a 2.6 kG field is not unreasonable. Again, if necessary one can redesign the lattice to provide more space for a longer kicker.

With a 10 cm kick, the septum can be 0.5 cm thick. The septum is pulsed to a half 60 Hz sine-wave. The peak field can be as high as 18 kG, and the total length can be as long as 21 m spanning the entire length of the straight section. At the end of the septum the beam will be displaced some 65 cm from the central orbit which is adequate to clear the downstream D_2 quadrupole. The extracted beams are, then, transported by higher field dipoles and quadrupoles to converge on targets located at the center of the ring.

We note that in this scheme there are 10 simultaneous extraction systems and 10 extracted beam lines - one per sector of the ring. Two beam bunches separated by 0.415 msec are extracted into each beam line. Somewhere in each beam line the two beam bunches should be switched to go in different branches so that all 10 bunches No. 1 will converge on target No. 1 at the center of

reactor vessel No. 1 and all 10 bunches No. 2 will converge on target No. 2 in vessel No. 2. The two vessels may be separated (say, vertically) by tens of meters.

E.   Summary

We have given here a conceptual design of an accelerator system which will produce twenty 150-GeV U^+ beam segments every 1/2 sec. Each segment is 10 nsec long with a current of 400 A. The emittances are such that each beam can be focused to a 1 mm radius spot 10 m away from a focusing element with an aperture radius of 30 cm. Ten of these beam segments hitting a DT target on two spots, five segments on each spot, will satisfy the requirements for initiating inertially confined fusion.

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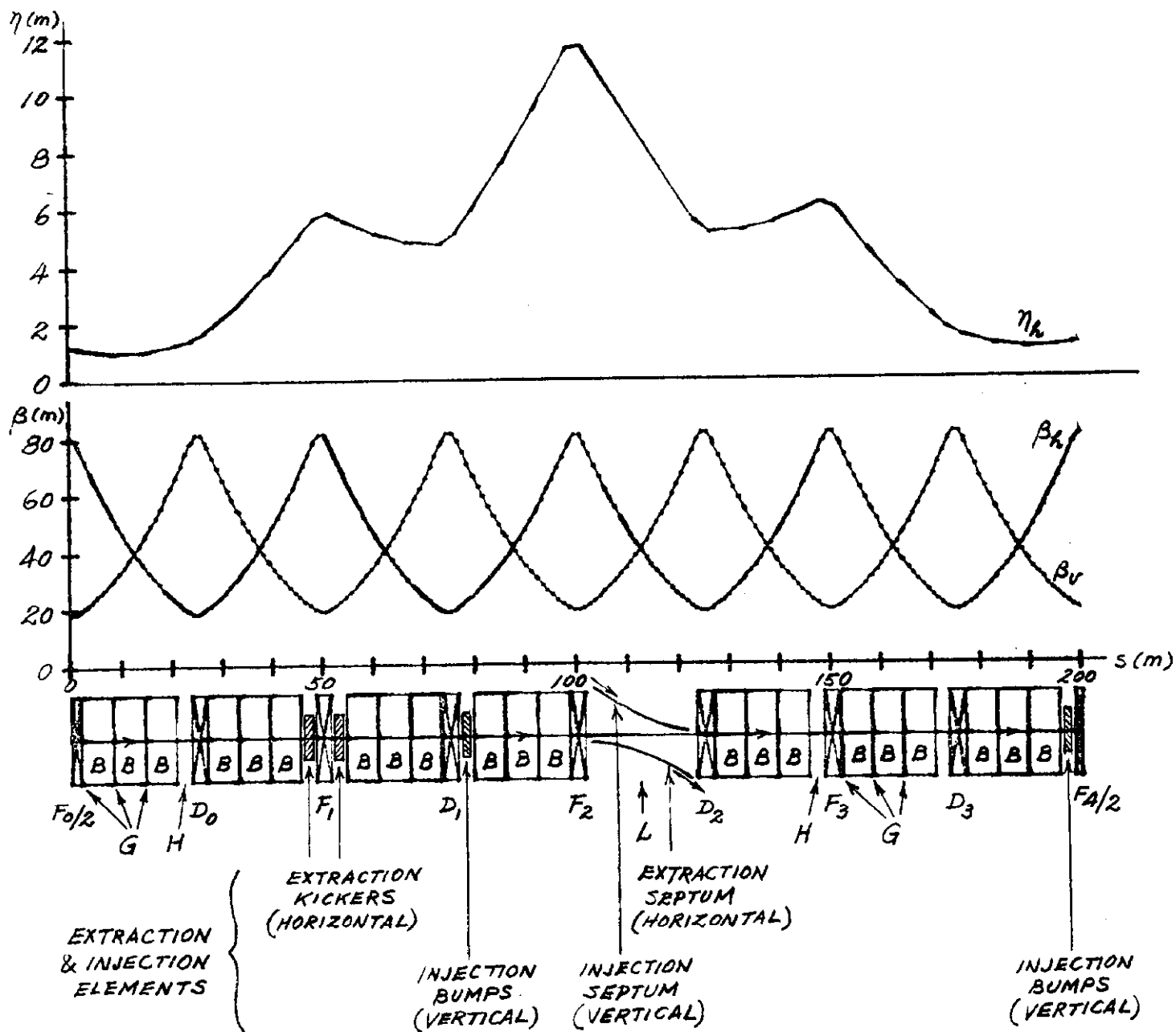
Figure 1. One sector (4 cells or 1/10 of ring) of the
           synchrotron lattice showing also the extraction
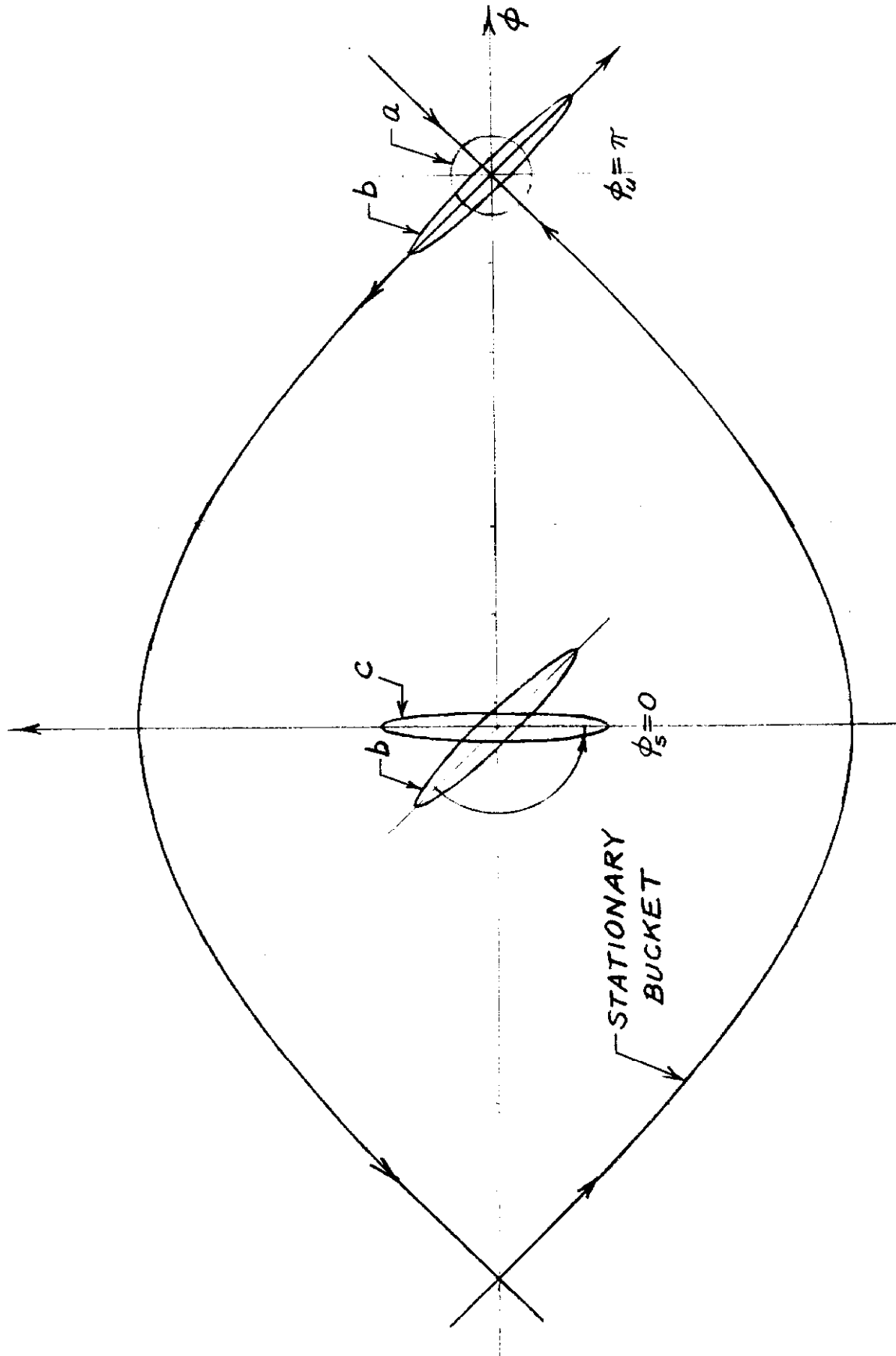   and the injection elements.

Figure 2. Longitudinal phase-space diagram illustrating the procedure of beam bunching on the defocusing rf phase (ϕ_u).